Eclogite facies metultramafite from the Veporic Unit (Western Carpathians, Slovakia)

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Abstract: Metultramafic rocks closely associated with eclogites in the Veporic unit of the Western Carpathians record a complex P–T evolution, including the effects of high-pressure (HP) metamorphism. The investigated metultramafite is chemically similar to pyroxenite, has a fine-to medium-grained texture, is composed predominantly of olivine and amphibole, and contains minor amounts of garnet, orthopyroxene, spinel, chlorite and carbonates. The high-pressure mineral assemblage is garnet (X_Mg = 0.46–0.47) + olivine (X_Mg = 0.71–0.73) + low-Al orthopyroxene (X_Mg = 0.77–0.78) + ilmenite + chlorite (X_Mg = 0.87–0.89) + Cr-spinel. Chromium-rich spinel is most likely a relict from the pre-HP metamorphic stage, possibly of magmatic origin. Calculations using a garnet–orthopyroxene Fe–Mg exchange thermometer, Al-in-orthopyroxene barometer, and thermodynamic modelling in the system SiO_2–TiO_2–Al_2O_3–FeO–MgO–CaO–H_2O indicate that the peak conditions of metamorphism reached 2.4±0.4 GPa and 702±20 °C.

Keywords: Metultramafite, eclogite, high-pressure metamorphism, subduction, Western Carpathians.

Introduction

“Orogenic” or “Alpine-type” peridotites represent mantle fragments that were tectonically incorporated in collisional mountain belts worldwide. These peridotite complexes commonly experienced high-pressure (HP) and ultrahigh-pressure (UHP) metamorphism that stabilized garnet in the various ultramafic lithologies, which include lherzolites, harzburgites, wehrlites, dunites and pyroxenites. In some instances, these ultramafic rocks, which are commonly associated with eclogites, were transferred from an overlying mantle wedge into subducting continental and oceanic crust, where all rock types experienced HP conditions that stabilized garnet in ultramafic rocks (garnet peridotite), omphacite in mafic rocks (eclogite), and coesite in silicic rocks (Brueckner & Medaris 2000; Scambelluri et al. 2010). Alternatively, lower-pressure spinel peridotites may be carried to deeper levels within a subducting host continental slab and develop garnet-bearing assemblages at HP (Medaris & Carswell 1990) or HP/UHP metamorphic conditions (e.g., Van Roermund & Drury 1998; Zhang et al. 2003; Janák et al. 2006; Faryad 2009). A third scenario is one in which ultramafic crystal cumulates (e.g., ophiolite components or ultramafic differentiates of mafic intrusions) were subducted “ab initio” together with other crustal rocks to HP conditions, producing garnet peridotites (e.g., Goddard et al. 1996; Ravna et al. 2006). Note that in all three of these tectonic situations, mafic rocks associated with peridotites are transformed to eclogite.

The pre-Alpine basement of the Western Carpathians represents an important segment of the Variscan orogeny in Europe, which marks the collision of Laurasia with Gondwana-affiliated terranes during the Paleozoic. Evidence for pre-Alpine subduction and high-pressure metamorphism is provided by eclogites, which are mostly retrogressed to garnet amphibolites and occur in all major tectonic units – Tatric, Veporic and Gemiceric (Hovorka & Méres 1990; Hovorka et al. 1992; Janák et al. 1996, 2007, 2009; Janák & Lupták 1997; Faryad et al. 2005, 2020). Metultramafic rocks occur sporadically in the pre-Alpine basement complexes of the Western Carpathians (Hovorka 1994; Koríkovský et al. 1998) but typical “Orogenic” or “Alpine-type” garnet peridotites of mantle origin are unknown.

Following our previous study of eclogites (Janák et al. 2007), we have investigated rare, garnet-bearing metultramafic rock associated with eclogites in the leptyno-amphibolite complex (LAC) of the North Veporic unit. Described here are the textures, mineral assemblages, and mineral compositions of a sample of garnet–orthopyroxene–olivine–amphibole metultramafite. The peak P–T conditions evaluated by conventional thermobarometry and thermodynamic modeling are...
similar to those of accompanying eclogites, revealing that both lithologies experienced high-pressure metamorphism, most probably during the Variscan orogeny.

**Geological background**

The investigated metaultramafic rocks occur in the northern part of the Veporic unit (Fig. 1), where the pre-Alpine basement is overlain by an Upper Paleozoic–Triassic sedimentary cover. The magmatic and metamorphic history of the Veporic unit was polyphase, comprising pre-Variscan, Variscan, Permian and Alpine events (e.g., Bezák et al. 1993; Plašienka et al. 1997, 2016; Putiš et al. 1997; Janák et al. 2001; Jeřábek et al. 2008a,b; Vojtko et al. 2016; Plašienka 2018).

The northern part of the Veporic unit is composed of several basement complexes covered by Permian and Mesozoic rocks (Fig. 1). The eclogites are part of the basement that is variously referred to as the Hron complex (Klinec 1966), leptyno-amphibolite complex (Hovorka et al. 1994, 1997) or layered metagnueous complex (Putiš et al. 1997). In this paper we use the term “leptyno-amphibolite complex” (LAC). In the investigated area, the LAC is composed of several rock types, the most abundant of which are amphibolites and gneisses (both ortho- and para-gneisses) that are strongly deformed and retrogressed to epidote amphibolites, mica.

![Fig. 1. Simplified geological map of the northern parts of the Veporic unit showing the locations of metaultramafite (star) and eclogite (circle) modified from Biely et al. 1992.](image-url)
schists and phyllites. Garnet amphibolites with relics of eclogites and ultramafic rocks (olivine gabbro, troctolite) occur in sporadic outcrops of metre to tens of metres size (Ivan et al. 1996; Mérès et al. 1996; Janák et al. 2007). Pre-Alpine granitoids and associated gneisses and mica schists belonging to the Kráľova hoľa complex were strongly affected by Alpine mylonitization. The intrusion age of these granitoids is 350 Ma, based on SHRIMP dating of zircons (Gaab et al. 2006). The Predná hoľa complex is composed of phyllites, metasandstones, basic volcanics and volcanoclastics that were recrystallized at low grades of metamorphism. Permian rocks include metamorphosed conglomerates, sandstones, arkoses and greywackes locally with volcanogenic material. Mesozoic rocks consist of Triassic carbonates and quartzites that were affected by low-grade metamorphism in Cretaceous time (Lupták et al. 2003).

Petrography and mineral chemistry

The investigated sample VV255 occurs as a loose block of ca. 1–1.5 m size within the LAC in the Krivuľa valley, Low Tatra Mountains (Fig. 1). This metaultramafic rock (Fig. 2) has a medium-grained granoblastic texture and is composed predominantly of olivine and amphibole. Accessory spinel is zoned, with green spinel containing cores of brown spinel (Fig. 3). Minor mineral phases include orthopyroxene, garnet, chlorite, ilmenite and carbonates. Unlike typical gabbroic
rocks (olivine gabbro, troctolite) within the LAC in the area (Ivan et al. 1996), the investigated metaultramafite shows no corona texture or remnants of plagioclase.

The compositions of the main mineral phases were determined using a CAMECA SX-100 electron microprobe at Dionýz Štúr Institute of Geology in Bratislava. Analytical conditions were 15 kV accelerating voltage and 20 nA beam current, with a peak counting time of 20 seconds and a beam diameter of 2–10 μm. Raw counts were corrected using a PAP routine. Calibration standards included natural minerals (Si, Ca: wollastonite, Na: albite, K: orthoclase, Fe: fayalite, Mn: rhodonite), pure element oxides (TiO₂, Al₂O₃, Cr₂O₃, MgO), and metals (Ni). Mineral abbreviations are according to Whitney & Evans (2010).

Garnet occurs as tiny irregular grains or accumulations of several grains (Fig. 4). The composition of garnet is relatively...
homogenous ($X_{\text{typ}}=0.37–39$, $X_{\text{Aln}}=0.42–0.44$, $X_{\text{em}}=0.15–0.18$, $X_{\text{sp}}=0.3–0.04$) with $X_{\text{Typ}}=\text{Mg}/(\text{Mg}+\text{Fe})$ ranging from 0.46 to 0.47 (Table 1). Orthopyroxene (Fig. 4) has a composition with $X_{\text{Typ}}=0.77–0.78$ and $\text{Al}_{2}\text{O}_{3}=0.5–1.0$ wt. %, with the lowest Al concentrations (0.02–0.03 apfu) occurring in the cores of the grains (Table 2). Olivine occurs as anhedral grains (Fig. 4), with a nearly homogeneous composition ($X_{\text{Typ}}=0.71–0.73$; Table 3). Spinel occurs in two textural varieties: discrete anhedral grains of variable size (~100–500 μm) and small (~20 μm) anhedral grains in symplectite (Fig. 4). Discrete spinel is continuously zoned from brown, chromian spinel cores (Spl1) to green, aluminous rims (Spl2; Fig. 4), whose compositions decrease in Cr* number (=100×Cr/(Cr+Al)) from 37 in cores to 5–6 in rims (Figs. 5, 6; Table 4). Aluminous spinel (Cr*≈2–3) occurs in symplectites (Fig. 4), where hornblende and orthopyroxene (Al$_2$O$_3$≥1 %) replace garnet and olivine. Ilmenite inclusions are common in spinel and tend to be located in the aluminous rims (Fig. 4); ilmenite occurs also in the matrix. Chlorite, carbonate and pale green amphibole are present in the matrix (Fig. 4); chlorite is Mg-rich with $X_{\text{Typ}}=0.88–0.90$ (Table 4), carbonate is mostly dolomite, and amphibole is hornblende (Table 5).

Metultramafite whole–rock geochemistry

Whole-rock analysis determined by the ICP–ES/MS method (Bureau Veritas, Canada) yields the following major element composition: SiO$_2$=43.20, TiO$_2$=1.74, Al$_2$O$_3$=7.84, Cr$_2$O$_3$=0.30, FeO$_{\text{tot}}$=13.90, MgO=22.10, CaO=8.54, Na$_2$O=0.67, K$_2$O=0.17 (wt. %), which lies within the picrite-melmesite compositional fields (Fig. 7) according to the chemical classification of Le Bas (2000). However, these terms refer to volcanic rock types, and there is no evidence that the sample had a volcanic origin. Consequently, the Veporic “ultramafite” has been compared with other Variscan ultramafic rock types, including Veporic eclogite, eclogite and garnet pyroxenite layers in peridotite in the Gříšil nappe, Moldanubian zone, Bohemian Massif (Medaris et al. 1995), eclogites from the Mariánské Lázně metaophiolite complex at the boundary between the Saxothuringian and Teplá–Barrandian terranes.

Table 1: Representative el. microprobe analyses of garnet.

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<tr>
<th>Element</th>
<th>Sample</th>
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<th>TiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Cr$_2$O$_3$</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
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<td>Typical</td>
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<td>40.42</td>
<td>0.06</td>
<td>22.20</td>
<td>0.44</td>
<td>19.91</td>
<td>1.31</td>
<td>9.59</td>
<td>6.60</td>
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<tr>
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<td>0.14</td>
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<td>0.33</td>
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<td>1.31</td>
<td>9.59</td>
<td>6.60</td>
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12 Oxygens

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Table 3: Representative el. microprobe analyses of olivine.

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<th>Ti</th>
<th>Al</th>
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<th>Mn</th>
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<th>Total</th>
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4 Oxygens

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<th>Ti</th>
<th>Al</th>
<th>Fe</th>
<th>Mn</th>
<th>Mg</th>
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<td>0.001</td>
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<td>0.000</td>
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<tr>
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<td>0.000</td>
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<tr>
<td>Maximum</td>
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<td>0.000</td>
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<td>0.000</td>
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Table 2: Representative el. microprobe analyses of orthopyroxene.

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<th>Cr$_2$O$_3$</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
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<td>28.40</td>
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<td>0.44</td>
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* $X_{\text{Typ}}=\text{Mg}/(\text{Mg}+\text{Fe})$
Bohemian Massif (Beard et al. 1995), and eclogites in the pre-Alpine nappe stack of the Getic–Supragetic basement, South Carpathians (Medaris et al. 2003). The whole rock composition of the Veporic metaultramafite lies within the combined compositional field for eclogite–pyroxenite–peridotite suites (Fig. 7). In general, it has a closer chemical similarity to pyroxenite, rather than eclogite, except that it has a higher TiO₂ content than the pyroxenites, and its Mg# is at the boundary between those for pyroxenites and eclogites.

**P–T conditions**

Peak metamorphic $P$–$T$ conditions have been calculated using conventional geothermobarometry and thermodynamic modelling.

A combination of the garnet–orthopyroxene Fe–Mg exchange thermometer (Harley 1984), and the Al-in-orthopyroxene barometer (Brey & Köhler 1990) was applied, using the compositions of garnet with the highest pyrope content and orthopyroxene with the lowest Al content. Due to the uncertainties in Fe$^{3+}$ concentrations in these phases obtained via electron microprobe analysis, all Fe is taken to be Fe$^{2+}$ in the calculations.

Application of the garnet–orthopyroxene geothermometer together with the Al-in-orthopyroxene geobarometer yields
ECLOGITE FACIES METAULTRAMAFITE FROM THE VEPORIC UNIT (WESTERN CARPATHIANS, SLOVAKIA) 215

Table 4: Representative el. microprobe analyses of chlorite and spinel.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chl</th>
<th>Chl</th>
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<tr>
<td>Cr₂O₃</td>
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<td>0.09</td>
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<td>0.05</td>
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<td>86.8</td>
<td>100.06</td>
<td>100.01</td>
<td>99.51</td>
</tr>
</tbody>
</table>

Oxygens
- 14
- 14
- 14
- 14
- 14

Si 3.138 2.818 2.929 0.001 0.003
Ti 0.11 0.009 0.02 0.125 0.686 0.06
Fe 0.598 0.528 0.541 0.582 0.953 0.579
Mn 0.005 0.002 0.005 0.008 0.003
Ca 0.009 0.009 0.006 0.001 0 0
Na 0 0 0 0 0
K 0 0 0 0 0
Total 9.896 9.966 9.957 3 3 3

Xₘg = Cr(Cr+Al)
Cr* = Cr(Cr+Al)

Discussion

The textural characteristics and thermobarometric results for the investigated garnet-bearing ultramafite reveal a complex P–T evolution.

The assemblage garnet + olivine + low-Al orthopyroxene + ilmenite + Mg-rich chlorite + Cr-spinel is interpreted to represent the stable mineral assemblage at peak metamorphic conditions. Cr-spinel may represent a mineral relict from the pre-HP metamorphic stage (Splat), possibly of magmatic origin, although it may have been stable at peak metamorphic conditions because chromium shifts the spinel–garnet transition towards higher pressures (Klemme 2004). Garnet crystallized from lower pressure phases during prograde metamorphism via a reaction such as,

\[ \text{Spl}_1 + \text{high-Al Opx} + \text{Cpx} \rightarrow \text{Grt} + \text{Ol} + \text{low-Al Opx} + \text{Spl}_2 \]

Due to decompression during exhumation, Cr-spinel (Spl₁) was transformed to Al-spinel (Splat) and garnet was replaced by Al-spinel, high-Al orthopyroxene, and amphibole. Continued decompression and cooling led to formation of abundant amphibole in the matrix. Consequently, the high-pressure metaultramafite has been extensively retrograded in the amphibolite facies and the rock now consists largely of amphibole and olivine.

Peak P–T conditions of metaultramafite are similar to those of the associated eclogites (2.5 GPa, 700 °C; Fig. 9), thus providing further evidence for high-pressure metamorphism in the pre-Alpine basement of the North Veporic unit. Although the timing of eclogite facies metamorphism has not yet been determined, existing data support a pre-Alpine age. Microprobe dating of monazite from the kyanite-bearing para- and ortho-gneisses in the northern Veporic unit (Janák et al. 2002) yielded two groups of ages. The older one (ca. 470 Ma) is interpreted as recording pre-Variscan (Ordovician) magmatism, whereas the younger one (ca. 340 Ma), as Variscan (Carboniferous) metamorphism. In addition, zircon grains in orthogneisses also reveal a Variscan (Carboniferous)
Fig. 7. Whole–rock analyses of Variscan eclogites and pyroxenites: Gföhl ecl and Gföhl pxite — eclogite and pyroxenite layers in massif peridotites in the Moldanubian Gföhl nappe, Bohemian Massif; ML ecl — eclogite in the Mariánské Lázně complex, Bohemian Massif; Rom ecl — eclogites in the pre-Alpine nappe stack of the Getic–Supragetic basement, South Carpathians, Romania; Veporic — eclogite and metaultramafite of this investigation.
metamorphic overprint (Gaab et al. 2006; Putiš et al. 2008), and Ar–Ar data on amphiboles from the northern Veporic unit yield mostly pre-Alpine ages (Kráľ et al. 1996). In contrast to Variscan metamorphism, Alpine metamorphism resulting from crustal thickening in Cretaceous time attained maximum P–T conditions of 1–1.2 GPa and 600–620 °C in the southern part of the Veporic unit (Janák et al. 2001; Jeřábek et al. 2008b, 2012). To summarize, P–T conditions and available age data suggest that the high-pressure rocks in the northern part of the Veporic unit were subducted to depths of about 80 km during the Variscan orogeny.

Variscan metamorphism is well documented in the pre-Alpine basement complexes of the Tatric unit where Alpine recrystallization was relatively weak. Variscan structure is preserved in the Western Tatra, where a high-grade unit comprising eclogites, kyanite-bearing gneisses and migmatites has been thrust top-to-the south over a lower-grade mica schist unit, showing an inverted metamorphic sequence (Janák 1994; Janák et al. 1996, 1999). The Sm/Nd dating of garnet from eclogite in the Western Tatra yields an age of 342 Ma (Moussallam et al. 2012). It is therefore inferred that HP metamorphism resulted from subduction in Variscan time. Similar, southward thrust vergency of the Tatric and Veporic pre-Alpine basement complexes has been considered to reflect exhumation of the LAC along a northward dipping subduction zone (Bezák et al. 1997; Putiš et al. 1997). In this case, the LAC represents the overriding plate with segments of the lower continental crust including eclogites (Hovorka et al. 1997) that were involved in the subduction zone. Faryad et al. (2020) proposed that the LAC was exhumed either along a hypothetical subduction zone located within the Tatric–Veporic realm or along the “Rakovec suture” (a suture zone formed by the closure of a Devonian oceanic basin), prior to the Upper Carboniferous. It should be noted that the eclogite investigated by Faryad et al. (2020) occurred as a pebble in Upper Carboniferous conglomerate from Rudňany in the Gemeric unit.

The pre-Alpine basement of the Western Carpathians has been affected by Alpine tectonic events, and its original position and connection to the Variscan orogenic belt in Europe is uncertain. Similarities to the Bohemian Massif have been recognized in high-grade metamorphic rocks exposed in the Tatra Mountains (Moussallam et al. 2012), suggesting an eastern extension of the Moldanubian unit. Southeast of the

Fig. 8. P–T section of the metaultramafite in the system CFMASTH (CaO=9.0, FeO=10.30, MgO=32.39, Al2O3=4.54, SiO2=42.5, TiO2=1.29 mol. %, H2O in excess) with compositional isopleths of garnet, orthopyroxene, olivine and chlorite at the peak metamorphic stage (ellipse). Results from conventional geothermobarometry (cross) are also shown. See text for more details.

\[
\begin{align*}
X_{Mg\,Grt} &= 0.46-0.47 \\
X_{Mg\,Opx} &= 0.77-0.78 \\
X_{Mg\,Olv} &= 0.71-0.73 \\
X_{Mg\,Chl} &= 0.87-0.89 \\
Al\,O_{Opx} &= 0.02-0.03
\end{align*}
\]
Western Carpathians, evidence for Variscan subduction is provided by occurrences of (U)HP rocks (eclogites, garnet peridotics) of Variscan age, e.g. in the Rhodopes (Janák et al. 2011) and the Southern Carpathians (Medaris et al. 2003).

Conclusions

The investigated metultramafite from the Veporic unit shows eclogite facies, high-pressure metamorphism. This is manifested by a peak metamorphic mineral assemblage of garnet \((X_{Mg}=0.46–0.47)+\) olivine \((X_{Mg}=0.71–0.73)+\) low-Al orthopyroxene \((X_{Mg}=0.77–0.78)+\) Al\(-\)ilmenite\(+\)chlorite \((X_{Mg}=0.87–0.89)+\) Cr-spinel; metamorphic \(P–T\) conditions reached 2.4±0.4 GPa and 702±20 °C GPa. Decompression and retrogression from the HP stage is manifested by the formation of more aluminous orthopyroxene, Al-spinel and abundant amphibole (hornblende). Metultramafic rocks in the North Veporic unit thus provide further evidence for high-pressure metamorphism, probably of Variscan age, in the pre-Alpine basement of the Western Carpathians.

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